Chapter 4
Sediment Budget and Shoaling Rates

4-1. Introduction

a. Inlet systems represent a primary natural boundary or sink for transport of littoral and nearshore sediment. Geomorphic features associated with inlets separate adjacent beach and backshore environments and act as conduits for exchange of water and sediment between lagoon or estuarine environments and the nearshore. As such, characteristic shoal deposits form in response to wave and current interaction as water and sediment ebb and flood through primary and secondary inlet channels (see Chapter 2). Depending on the dominance of wave processes versus tidal currents, sediment deposition from cross-shore and longshore sources varies spatially, from within the lagoon or estuary (flood shoal) to seaward of the entrance (ebb shoal), and temporally as shoal migration in response to seasonal shifts in wave height and direction, and storm events. Regardless of feature characteristics within the inlet system, in most cases, this environment is a natural sink for coastal sediment. Consequently, the application of a sediment budget to inlets and adjacent environments is an effective approach for evaluating the relative significance of various sediment sources contributing to shoal growth and the relative importance of sediment bypassing from the shoals to adjacent beaches.

b. Assessing the sediment budget is particularly important where engineering activities, such as jetty construction and dredging, have fixed the position of the channel. This analysis assists scientists and engineers with quantifying the dynamic response of inlet systems by identifying relevant coastal processes and estimating volume rates of littoral transport. Engineering design, construction decisions, and management plans affect, and are affected by, sediment budget considerations. Predicting downdrift shoreline response and channel shoaling rates is crucial to efficient system maintenance efforts. This chapter reviews the components of a coastal sediment budget and presents an example of a sediment budget for engineering application. Shoaling rate prediction methods will also be discussed. Channel shoaling is an important component of the inlet system, and its prediction is critical to effective maintenance of the navigation channel.

c. Primary references on coastal sediment budgets include *Beach Processes and Sedimentation* (Komar 1976), the *Shore Protection Manual* (SPM 1984), Engineer Manual (EM) 1110-2-1502 entitled *Coastal Littoral Transport*, and Instruction Report CERC-93-1 entitled *Review of Geologic Data Sources for Coastal Sediment Budgets* (Meisburger 1993). Although none of these specifically focuses on inlet systems (i.e., the inlet system is usually the unknown portion of the sediment budget), most of the information presented in these documents is applicable to any coastal setting.

4-2. Components of a Coastal Sediment Budget

a. Sources and sinks.

(1) A sediment budget reflects an application of the principle of continuity or conservation of mass to coastal sediment. The time rate of change of sediment within a system is dependent upon the rate at which material is brought into a control volume versus the rate at which sediment leaves the same volume (Komar 1976). The budget involves assessing the sedimentary contributions and losses and equating these to the net balance of sediment in a coastal compartment. Any process that results in a net increase in sediment in a control volume is called a *source*. Alternately, any process that results in a net loss of sediment from a control volume is considered a *sink*. Some processes can function as sources and sinks for the same control volume (e.g., longshore sediment transport).

(2) The balance of sediment between losses and gains is reflected in localized erosion and deposition. Table 4-1 summarizes possible sources and sinks of sediment for a coastal sedimentary budget. In general, longshore movement of sediment into a coastal compartment, onshore transport of sediment, additions from fluvial transport, and dune/bluff/cliff erosion provide the major sources of sediment. Longshore movement of sediment out of a coastal compartment, offshore transport of sediment, and aeolian transport and washover that increase beach/island elevation produce losses from a control volume. Further discussion regarding the type and importance of sources and sinks for evaluating a coastal sediment budget are discussed in detail in Komar (1976), the *Shore Protection Manual* (SPM 1984), and Meisburger (1993).

(3) All elements of sediment budgets do not necessarily have the same spatial characteristics. For instance, tidal inlets often function as *point* sinks or features that decrease the transport of sediment across a *limited* portion of a control volume boundary. Conversely, a *line* sink causes a decrease in sediment transport across an *extended* portion of a control volume. Net transport of sediment offshore and out of the control volume along the entire

Table 4-1
Sources and Sinks for a Coastal Sediment Budget (after Bowen and Inman (1966))

Sources	Sinks
· Longshore transport of sediment into a control area	· Longshore transport of sediment out of a control area
· Onshore transport	· Offshore transport
· Fluvial transport	· Washover deposition
· Dune/bluff/cliff erosion	· Aeolian transport out of control area
· Aeolian transport onto beach	· Sediment storage in offshore shoals
· Biogenous and hydrogenous deposition	· Deposition in submarine canyons
· Beach replenishment	· Solution and abrasion
	· Dredging

offshore boundary is an example of a line sink. Unlike *point* sources or sinks that are quantified in units of volume per year, *line* elements of a sediment budget are calculated relative to the total length of shoreline over which the source or sink operates. Table 4-2 provides a classification of elements in a coastal sediment budget in terms of point and line sources or sinks. In a complete sediment budget, the difference between the addition of all source components and sediment removed from the control volume must total zero. However, in general applications, a sediment budget calculation is made to estimate an unknown erosion or deposition rate; the difference resulting from equating known sources and sinks. Detailed discussions on how gains and losses can be evaluated are given in SPM (1984) and EM 1110-2-1502, and an example of a sediment budget for engineering application is presented in Section 4-3.

b. Sediment budget boundaries. Boundaries for coastal sediment budgets are determined by the area under study (control volume), the time scale of interest, and the purpose of the study. For a given area, adjacent sediment compartments may be needed, with shore-perpendicular boundaries at significant longshore changes in the coastal system. At inlet systems, compartment boundaries are needed regardless of the magnitude and direction of shoreline response in adjacent compartments due to significant differences in processes affecting sediment transport. Although inlet systems can exchange sediment between updrift and downdrift beaches via shoal bypassing, most

Table 4-2
Classification of Elements in a Coastal Sediment Budget (after SPM (1984))

Location of Source or Sink	Offshore Side of Control Volume	Onshore Side of Control Volume	Within Control Volume	Longshore Ends of Control Volume
Point Source (volume/unit time)	Offshore shoal or island	Rivers, streams	Shoal erosion	Longshore transport into control volume
Point Sink (volume/unit time)	Offshore shoal; submarine canyon	Inlets	Dredging	Longshore transport out of control volume
Line Source (volume/unit time/unit length of coast)	Onshore transport	Coastal erosion of dunes, bluffs, and cliffs	Beach erosion; calcium carbonate production	NA
Line Sink (volume/unit time/unit length of coast)	Offshore transport	Washover; coastal land and dune storage	Beach accretion; beach nourishment; calcium carbonate losses	NA

NA - not applicable.

of the time this environment responds as a point sink for sediment, resulting in well-defined natural boundaries for a control volume. Shore-parallel boundaries also are needed on the seaward and landward sides of the control volume. The landward boundary is generally defined as a position representing the landwardmost extent of shoreline position for the temporal extent of the study, whereas the seaward boundary is established at or beyond the limit of sediment movement initiation (seaward edge of nearshore zone) or the limit of significant sediment movement due to steady wave action (closure depth) (Hallermeier 1981). Boundary criteria vary depending on study objectives. Therefore, it is critical that factors used to determine compartment boundaries be explicitly defined, such that the selection may be evaluated and compared with previously established sediment budgets.

c. Convection of littoral material. The magnitude and direction of coastal processes affect the classification of gains or losses to or from a control volume. For example, the net rate of sediment deposition or erosion in the littoral zone is controlled by differences in the rate of longshore transport into and out of a control volume. If sediment export is greater than import, erosion results and the compartment is a net source of material to adjacent compartments. Some processes may subtract at the same rate they add sediment to a control volume, resulting in no net change in material volume. The most important convecting process is longshore sediment transport. Along most coasts, gross longshore transport rates exceed net rates, and it is possible to have gross sediment transport rates in excess of 500,000 m^3 (650,000 yd^3) annually with no apparent beach changes. In other words, the same net rate of longshore sediment transport can be produced by widely varying rates of gross transport in and out of a control volume. Other convecting processes that may produce large rates of sediment transport with little noticeable change include tidal flows, especially around inlets, wind transport in the longshore direction, and wave-induced currents in the offshore zone. Because any structure that interrupts longshore sediment transport will normally result in erosion or accretion, it is important that the sediment budget quantitatively identify all processes convecting sediment through the study area.

d. Relative sea level change. Relative changes in sea level are the result of fluctuations in eustatic sea level (global water level adjustments) and regional or local changes in land level. Although eustatic sea level is rising worldwide, land levels are rising and falling due to tectonic forces, compactional subsidence, and human activities (i.e., subsurface fluid withdrawal). The importance of relative change in sea level on coastal engineering design depends on the time scale and the locality involved; impacts should be evaluated on a project-by-project basis. In terms of its impact on a coastal sediment budget, relative sea level change *does not* directly enter the evaluation procedure; however, the net effect of elevation changes may be landward (rising water level) or seaward (falling water level) displacement of the shoreline. Thus, relative changes in sea level can result in the appearance of a gain or loss of sediment volume. However, any changes in sediment volume would be balanced within the control volume because the seaward boundary of the compartment generally is defined by the seaward limit of significant sediment transport.

e. Summary. The range of significance for sinks, sources, and convective processes in a coastal sediment budget is described in Table 4-3. The relative importance of elements in the sediment budget varies with locality and with the boundaries of a particular control volume. For most beach environments, gross longshore transport rates significantly exceed other volumetric rates in the sediment budget, but if the beach is approximately in equilibrium, this may not be noticeable. Erosion of beaches, dunes, bluffs, and cliffs, as well as river contributions, are the principal natural sources of sediment in most locations. Human influences, such as beach nourishment, may provide major sources in local areas. Inlets, lagoons, and environments seaward of the depth of initiation of sediment motion comprise the principal natural sinks for coastal sediment. However, sediment transport or shoal migration from ebb-tidal deposits at inlets to the beach (Fitzgerald 1984), and erosion and offshore transport of sediment from estuaries and lagoons during major storm events (Isphording and Ismand 1991) illustrate the varying importance of sources and sinks for specific study areas. Of potential importance as either a sink or source is the offshore zone between closure depth and the point of initiation of sediment movement. Detailed analyses of historical bathymetric change on this portion of the continental shelf indicate significant sediment movement (Knowles and Gorman 1991; List, Jaffe, and Sallenger 1991; Byrnes and Hiland 1994), suggesting greater importance to the coastal sediment budget than originally anticipated.

4-3. Example Application

a. General.

(1) Coastal sediment budgets are particularly useful in assessing the possible impacts of engineering activities. For example, once a budget has been established for natural conditions at a study site, one can assess the

Table 4-3
Importance of Contributions to a Coastal Sediment Budget Relative to the Gross Longshore Sediment Transport Rate (after SPM (1984))

Sources	
Fluvial input	· Major source in limited areas where rivers carry sediment to the littoral zone; may contribute several times the gross longshore sediment transport rate during floods.
Dune, bluff, and cliff erosion	· Generally the major sources where river contributions are insignificant. Approximately 3 to 10 m^3/year (4 to 13 yd^3/year) per meter of beach.
Onshore transport	· Quantities uncertain. Net contributions can be estimated from historical bathymetric change data.
Aeolian transport	· Relatively unimportant as a source.
Beach replenishment	· Varies from 0 to greater than the gross longshore transport rate.
Calcium carbonate production	· A significant source in tropical climates. Approximately 0.5 m^3/year (0.7 yd^3/year) per meter of beach in temperate climates.
Sinks	
Inlets and lagoons	· May remove from 5 to 25 percent of the gross longshore transport rate per inlet. Depends on inlet size, tidal flow characteristics, and engineering influences.
Washover	· Less that 2.5 m^3/year (3.2 yd^3/year) per meter of beach, and limited to low-profile beach environments.
Offshore transport	· Quantity uncertain. Net contributions can be estimated from historical bathymetric change data.
Submarine canyons	· Where present, may intercept up to 80 percent of gross longshore sediment transport.
Aeolian transport	· Usually less than 5 m^3/year (6.5 yd^3/year) per meter of beach.
Dredging	· May equal or exceed gross longshore transport in some localities.
Convective Processes	
Longshore transport (waves)	· May result in accretion of gross longshore sediment transport, erosion of net longshore sediment transport, or no change depending on conditions of equilibrium.
Tidal currents	· May be important at mouth of inlet and vicinity, and on irregular coasts with a high tidal range.
Wind	· Longshore wind transport is important only in limited regions.

impact of nearshore sand mining on beach response, seawall placement on adjacent shoreline change, or jetty construction, which interrupts the longshore transport of sediment, on downdrift reaches of coast. Many examples of coastal sediment budget analyses exist (e.g., Bowen and Inman 1966; Caldwell 1966; Pierce 1969; Stapor 1973; Jarrett 1977; Headland, Vallianos, and Sheldon 1987; Jarrett 1991; Simpson, Kadib, and Kraus 1991; and others), however, the sediment budget presented below is of particular significance because an inlet system is a critical component of the analysis in the study area.

(2) As part of a feasibility and environmental assessment report for evaluating the impacts of harbor improvements at Morehead City, North Carolina, on regional coastal response, the U.S. Army Engineer District, Wilmington, summarized shoreline processes in the study area and performed a coastal sediment budget analysis to quantify the volumes of material moved by coastal processes (U.S. Army Engineer District, Wilmington 1990). The time period covered by the analysis was 1980 to 1988, and overall results of the budget were compared with previous studies to determine the impacts of a channel deepening project (1978) on adjacent shoreline response. The study area was divided into three reaches (Bogue Banks, Beaufort Inlet, and Shackleford Banks) (Figure 4-1). For each reach, average annual volume change rates due to coastal processes and dredging procedures were quantified. Longshore transport rates were then calculated using volume change rates in combination with relative energy flux values determined at the boundaries of the reaches through a wave refraction analysis. Although significant effort goes into developing a sediment budget, it must be remembered that it is an estimate that can be in error by a factor of two or more depending on the detail of knowledge of coastal processes in the study area and historical rates of shoreline and bathymetric response. In addition, sediment budgets are determined for varying periods of time and represent average rates of change for those time intervals. They

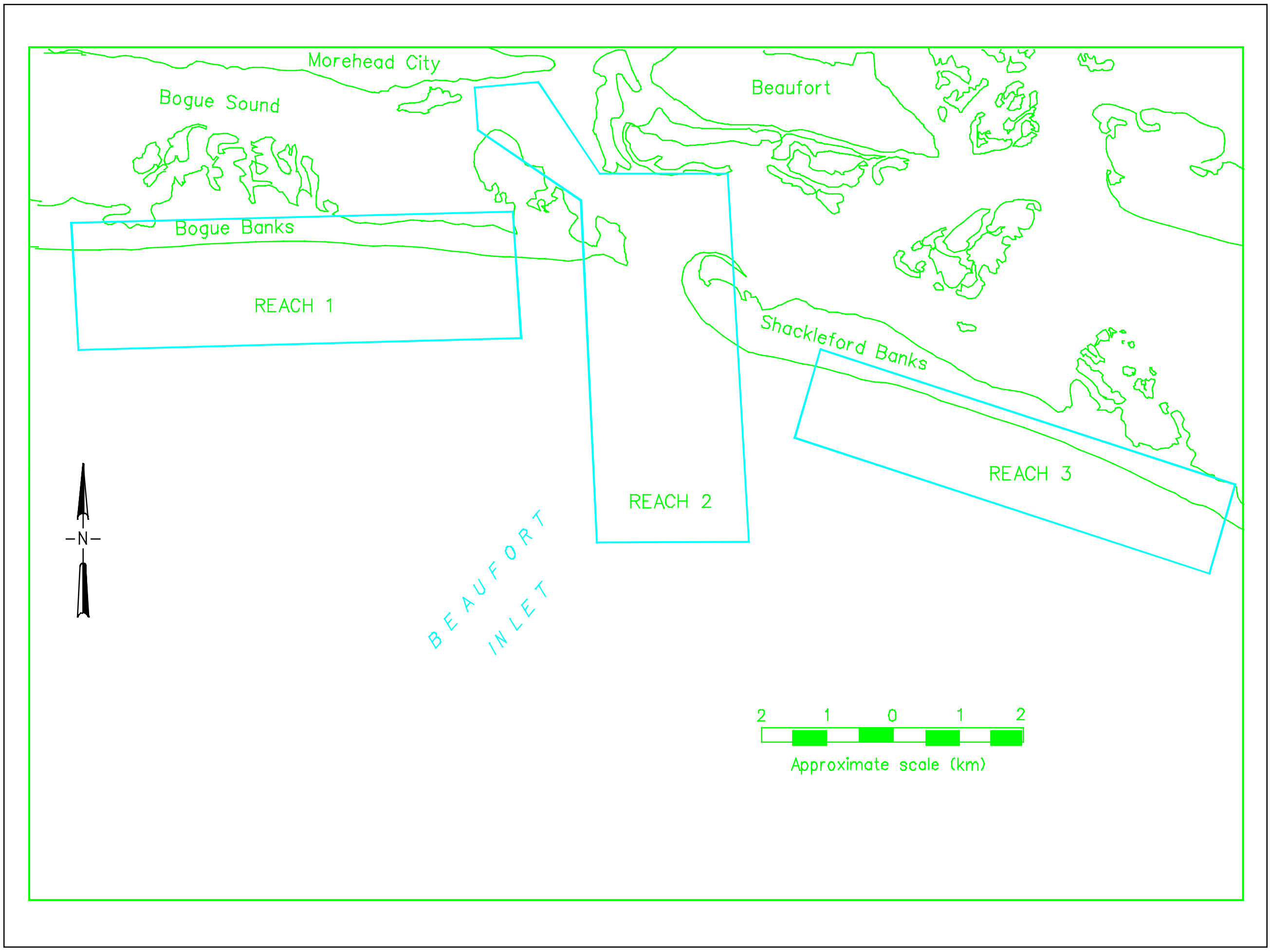

Figure 4-1. Study area showing the three sediment budget reaches

may not be indicative of changes in any one year. The following discussion is a summary of a revised sediment budget for the Beaufort Inlet area performed as part of a feasibility study for the Morehead Harbor Improvements project (U.S. Army Engineer District, Wilmington 1990), illustrating the practical use of this technique for assessing the potential impacts of engineering activities.

b. Environmental conditions. Wind-generated waves and currents, as well as tidal currents, are the primary processes affecting change in the study area. The study area is oriented east-west and predominant winds come from the southwest to south-southwest direction. Approximately 35 percent of the time, wind is blowing onshore with a mean speed of approximately 12 km/hr (7.5 mph). As such, the predominant direction of wave approach is from the southwest. Wave data used in the study were derived from Atlantic Coast Hindcast, Phase II Wave Information compiled by the Coastal Engineering Research Center for the period 1956 through 1975 (Station 42). Average significant wave height for this station is 1.3 m (4.3 ft); however, maximum wave heights of 4.7 m (15.5 ft) were predicted for the 20-year record. Mean tide level at Beaufort Inlet is 0.5 m (1.7 ft) with a mean tide range of 0.9 m (3.1 ft). The mean maximum flood current speed at the inlet channel entrance near Fort Macon (Figure 4-1) is 1 m/sec (2 knots), whereas the mean maximum ebb speed is 0.9 m/sec (1.8 knots). Note that these tide values are only averages; storm tidal heights and velocities can be four to five times higher.

c. Study site. The study area is located along the northeast margin of Onslow Bay (an open-ocean embayment between Cape Lookout and Cape Fear, NC), seaward of Morehead City, NC, and west of Cape Lookout. The three study reaches are included within an area approximately 21 km (13 miles) long (Figure 4-1) and contain fine sand barrier island beaches. Control volumes extend approximately 1,370 m (4,500 ft) offshore from the shoreline to an average depth of -10.7 m (-35 ft) MSL. The Bogue Banks reach extends 7,380 m (24,200 ft) in an east-west orientation, whereas the Shackleford Banks reach extends 7,100 m (23,300 ft) in a northwest-southeast direction. A groin constructed along eastern Bogue Banks at Fort Macon in the early 1850s is the only coastal structure present along the outer coast. The Beaufort Inlet reach is the largest control volume in the sediment budget study, encompassing the inlet channel, the Morehead City Harbor area, the ebb-tidal shoal, the Fort Macon beach area, and Shackleford Point.

d. Shoreline position and beach profile volume changes.

(1) The first component of a strategy for quantifying the sediment budget is to determine average annual volume change rates for each part of the study area. For the study at Beaufort Inlet and vicinity, volume changes were divided into two categories based on changes along the barrier island shorelines and changes associated with inlet and harbor areas.

(2) For the analysis period (1980-1988), profile data were available for quantifying volume changes associated with shoreline position change along Bogue and Shackleford Banks. Onshore and offshore sediment volume differences were calculated separately from the shoreline to an average depth of 10.7 m (35 ft) msl (≈1,370 m (4,500 ft) from baseline). The offshore length of the profile included the active littoral zone, such that differences calculated would indicate total volume changes. Rates of shoreline position change also were calculated from the beach profile data and compared favorably with existing change rates (see U.S. Army Engineer District, Wilmington (1990)). However, volume change information compiled prior to the interval 1980-1988 relied on comparisons of historical shoreline position for estimating volume rates of change. Consequently, sediment budget calculations performed for earlier time intervals may yield different results relative to variations in technique, regardless of natural changes.

(3) The onshore and offshore portions of the active beach profile on Bogue Banks showed accretion for the period 1980-1988. Shoreline movement averaged 22.0 ft/year, while onshore and offshore volume change averaged 132,000 and 255,000 m^3/year (172,000 and 334,000 yd^3/year), respectively (Figure 4-2). Overall, approximately 387,000 m^3/year (506,000 yd^3/year) of sediment accumulated in Reach 1 for the study period. Most of this increase in sediment volume was related to a beach replenishment project at Atlantic Beach in 1986 totaling

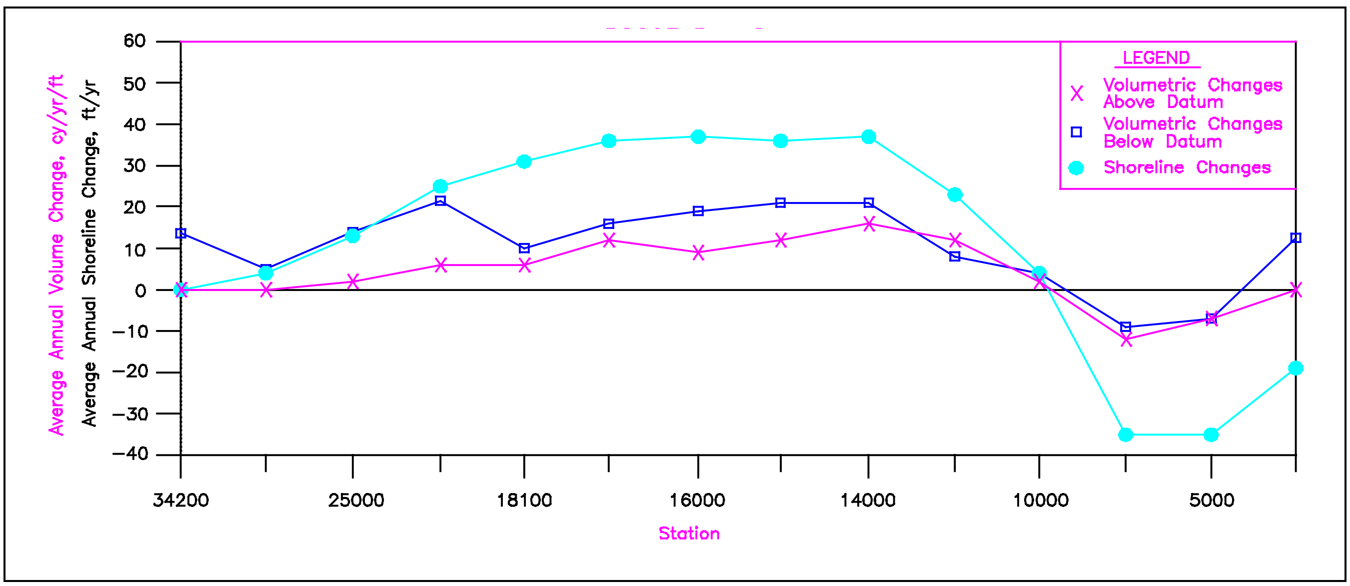

Figure 4-2. Shoreline position and volume change, Bogue Banks, NC

3.0 million m^3 (3.9 million yd^3). Annualized for the study time period, this volume of material amounts to a 373,000 m^3/year (488,000 yd^3/year) addition to the area.

(4) For Shackleford Banks, the magnitude of change was quite different. For the same time period, average shoreline movement showed net retreat (-0.70 m/year; -2.3 ft/year), and onshore volume change reflected this change (-23,000 m^3/year; -30,000 yd^3/year) (Figure 4-3). However, offshore profile volume change illustrated net accretion (95,500 m^3/year; 121,000 yd^3/year), resulting in a net addition of sediment to Reach 3 of 69,600 m^3/year (91,000 yd^3/year). Overall, the barrier island littoral zone compartments in the study area are stable for the time period of analysis.

e. Sediment volume changes near Beaufort Inlet.

(1) Shoreline changes within 610 m (2,000 ft) of Beaufort Inlet were included in the analysis of sediment volume changes in Reach 2 because shoreline movement in this area is influenced by inlet processes and responds differently than open-coast shorelines in Reaches 1 and 3. Beach profile data were supplemented using aerial photography digitized to determine area changes for Fort Macon and Shackleford Point.

(2) For the period 1978 to 1988, the Fort Macon region accreted at an average rate of 9,900 m^3/year (13,000 yd^3/year). Because only area and shoreline position change can be quantified using photography, volume change associated with shoreline adjustments had to be estimated based on change rates multiplied by the vertical distance between the shoreline and closure depth times the longshore distance covered by the control volume (SPM 1984). The estimated amount of change for the area was partially the result of deposition of 920,000 m^3 (1.2 million yd^3) of material in 1978.

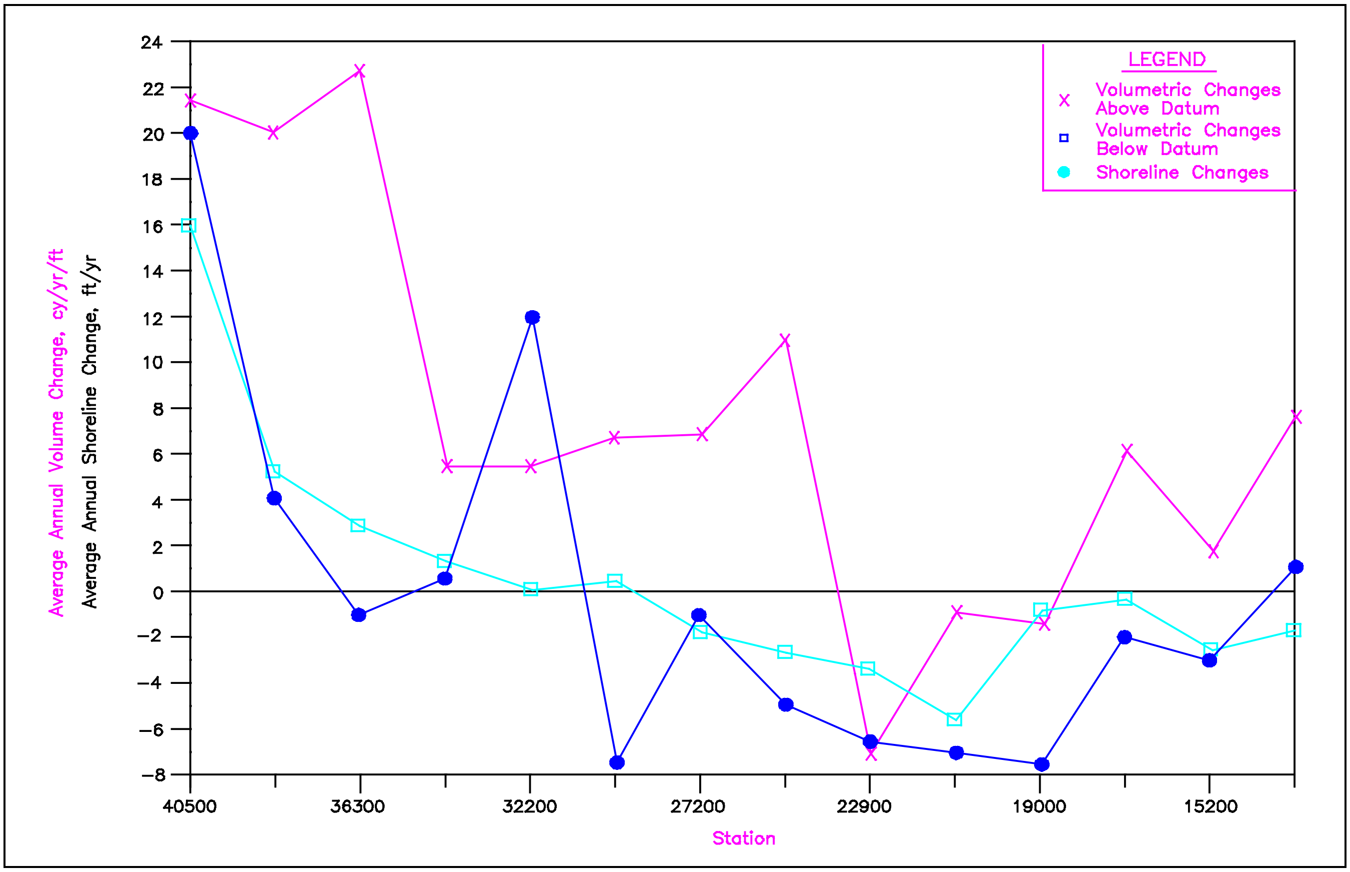

Figure 4-3. Shoreline position and volume change, Shackleford Banks, NC

(3) The western end of Shackleford Island (Shackleford Point) was analyzed for area change using aerial photography for the same time period as the Fort Macon shoreline. Using the same conversion procedures listed above, sediment volume change was estimated at -14,500 m^3/year (-19,000 yd^3/year), the opposite trend shown for the beach at Fort Macon.

(4) Sediment volume change on the offshore bar (ebb-tidal shoal) was considered one of the most critical components of the sediment budget because previous analyses indicated that the shoal was deflating at a rapid rate. Comparisons using digitized bathymetric data were made for the period 1974 to 1988 for an approximate 3.2-square-km (1.25-square-mile) area limited by the extent of the 1988 survey. After making adjustments for overlap with dredging activities and prorating net volume change to cover the same area included in the 1976 General Design Memorandum (GDM) sediment budget, it was determined that the net annual volume loss from the ebb-tidal shoal was 210,000 m^3 (274,000 yd^3). This value is slightly less than but consistent with that from the 1936 to 1974 sediment budget analysis. It was stated that if shoal deflation continued at its then current rate, it was possible that the wave climate impinging on the shoreline might change, causing increased wave energy and erosion. Volume changes for deposits in Back Sound were taken from the 1976 GDM and assumed representative for the period 1980 to 1988. This is supported by the fact that dredging volume in the inner harbor had not increased substantially since the harbor was deepened in 1978.

(5) Channel dredging is a large component of sediment movement in the inlet reach. Annual pipeline and hopper dredging volumes for this area are provided in U.S. Army Engineer District, Wilmington (1980) for the shoal, channel, and back-barrier navigation channel. From these data, the average annual dredge volume from the ebb-tidal shoal was determined to be approximately 550,000 m^3 (716,000 yd^3). Pipeline dredging volumes from interior channels behind the islands averaged 137,000 m^3/year (179,000 yd^3/year) for the period 1980 to 1988.

f. Wave energy flux analysis.

(1) Estimating the distribution of wave energy, particularly at the boundaries of coastal compartments, is an important component of any sediment budget analysis. To encompass the impacts of variable nearshore bathymetry on wave transformation along the coast, the finite-difference numerical model RCPWAVE (Ebersole, Cialone, and Prater 1986) was used to generate information on breaker wave height, breaker angle, and wave number. This information was used to predict wave energy flux at the break point so that potential sediment transport rates in and out of a sediment budget compartment, as well as at discrete longshore positions within a reach, could be calculated.

(2) Results from the analysis for the reaches along Bogue and Shackleford Banks indicated a relatively even distribution of wave energy. The eastern side of Bogue Banks is most influenced by waves out of the southwest, whereas the western portion of the island is more influenced by waves out of the east-southeast. Conversely, the shoreline response along Shackleford Banks primarily is controlled by waves from the south-southeast. Results obtained for areas near the margin of Beaufort Inlet show greater wave variability than those found along open-ocean beaches, likely the result of rapidly changing bathymetric contours that influence wave transformation and energy flux.

(3) Numerical model results also suggest that wave energy entering the inlet from the west is three times that coming from the east. For Bogue Banks, the energy flux from the west is relatively constant near the central portion of Reach 1 and then increases significantly towards the inlet. Along Shackleford Banks, very little energy is propagated from the east, due in part to sheltering by Cape Lookout. These trends are supported by inlet shoaling patterns which indicate that approximately 70 percent of sediment dredged from the Beaufort Inlet channel comes from the west. Total wave energy flux values at reach boundaries are used in the sediment budget equations presented in the next section to determine longshore sediment transport rates into and out of the inlet reach.

g. Sediment budget. After determining all the average annual volumetric change rates and the relative energy flux at reach boundaries, the parameters were combined by reaches to calculate three unknown annual volumetric rates: longshore transport rate (QE), volume rate bypassing to the east (BE), and volume rate bypassing to the west (BW). Table 4-4 provides a summary of known sediment budget volume change rates for each reach for the 1980 to 1988 time period. One sediment budget equation was established for each reach based on the information provided above. Coefficients for the longshore sediment transport (QE) values represent the relative energy flux values at reach boundaries. Figure 4-4 shows the volume relationships between the

Table 4-4
Sediment Budget Volume Change Rates (after U.S. Army Engineer District, Wilmington (1990))

Parameters	Volume Change m³/year	Volume Change yd³/year
Reach 1 - Bogue Banks		
Beach Replenishment (REPL)	+373,000	+488,000
Total Volume Change (VC1)	+387,000	+506,000
Reach 2 - Beaufort Inlet		
Channel Dredging Near Ebb-Shoal (DRED)	-548,000	-716,000
Dredging in Back Sound (BSND)	-137,000	-179,000
Back Sound Loss (from 1976 GDM) (BSND)	-44,000	-58,000
Fort Macon Volume Change (FMVC)	+9,900	+13,000
Shackleford Point Volume Change (SPVC)	-14,500	-19,000
Volume Change on the Ebb-Tidal Shoal (VC2)	-210,000	-274,000
Reach 3 - Shackleford Banks		
Total Volume Change (VC3)	+70,000	+91,000

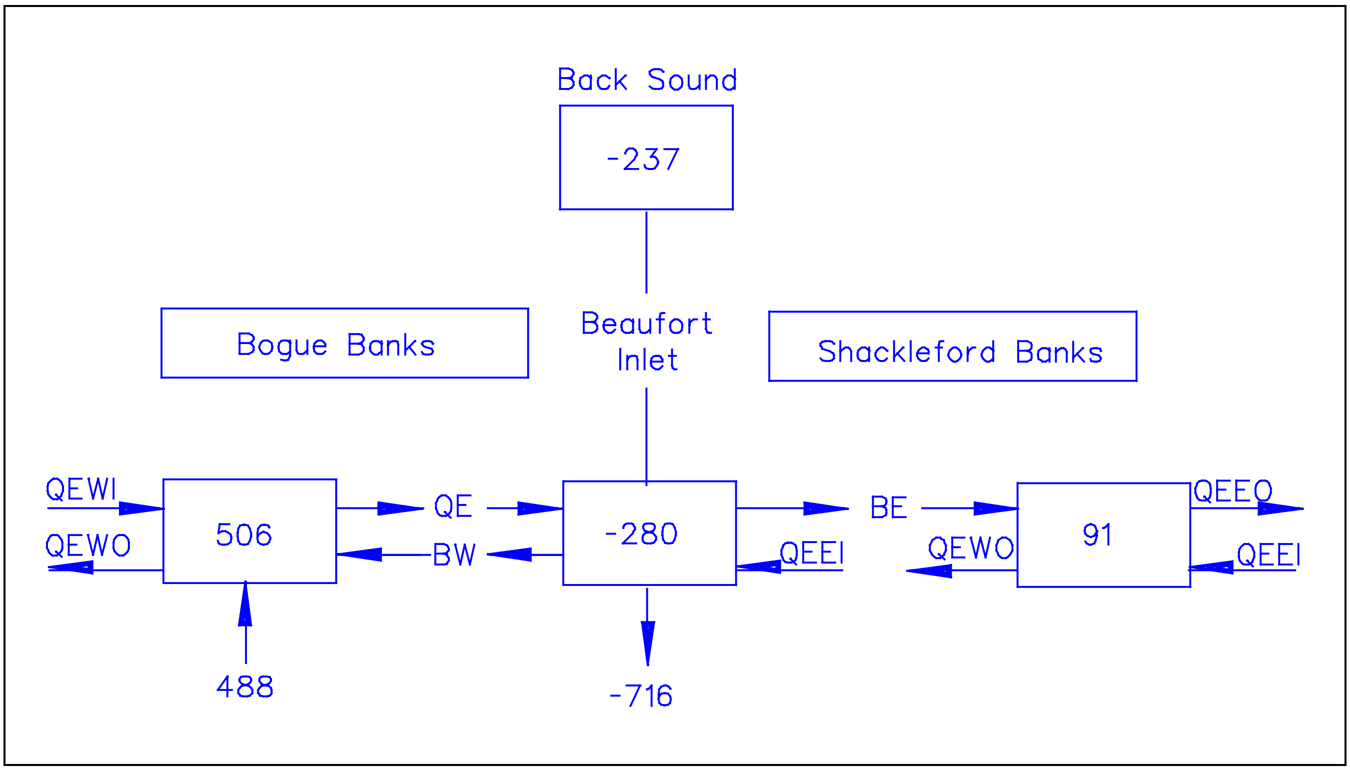

Figure 4-4. Sediment budget reaches and volumes (numbers × 765 m³/year (1000 yd³/year))

reaches. The following equations can be solved simultaneously to determine the three unknowns. They are:

Reach 1 - Bogue Banks

$$1.43\ QEWI - 0.29\ QEWO + REPL + BW - 1.0\ QEEO = VC1$$

$$0.14\ QE - 17 + BW = 0 \tag{4-1}$$

Reach 2 - Beaufort Inlet

$$0.29\ QEEI + 1.0\ QEWI - BSND - DRED - BE - BW = TVC2 \tag{4-2}$$

where

$$TVC2 = VC2 + FMVC + SPVC$$

$$1.29\ QE - 673 - BE - BW = 0$$

Reach 3 - Shackleford Banks

$$-0.65\ QEEO + 0.25\ QEEI + BE - 0.29\ QEWO = VC3$$

$$-0.69\ QE - 91 + BE = 0 \tag{4-3}$$

where

QEWI - transport into the reach, west side.

QEWO - transport out of the reach, west side.

QEEI - transport into the reach, east side.

QEEO - transport out of the reach, east side.

After inserting the values in Table 4-4 into the above equations and solving simultaneously, longshore transport (QE), transport bypassing to the east (BE), and transport bypassing to the west (BW) were determined as:

QE = 806,700 m^3/year (1,055,000 yd^3/year)

BE = 610,200 m^3/year (798,000 yd^3/year)

BW = -100,200 m^3/year (-131,000 yd^3/year)

The negative value for bypassing to the west indicates that the transport direction assumed in Figure 4-4 was opposite of the actual direction, suggesting that no sand is bypassing Beaufort Inlet from east to west.

h. Results of the analysis. Using measured volume change rates in combination with wave energy flux estimates provided a means of assessing the magnitude of longshore sediment transport and sediment bypassing at Beaufort Inlet. Two critical findings evolved from this analysis: 1) sediment was only bypassing the inlet from west to east, potentially providing material to beaches on Shackleford Banks, and 2) the ebb-tidal shoal area was deflating at a fairly rapid rate. Both of these observations were consistent with conclusions from previous studies. From these results, one can infer that certain human-induced processes may be adversely impacting the evolution of this coastal system relative to natural conditions. With this information, appropriate actions can be taken to alleviate future problems. Without performing a sediment budget analysis, pertinent findings may have been inadvertently missed.

i. Alternate approach. Increased capabilities in the areas of shoreline position change simulations (Grosskopf and Kraus 1994) and surface modeling software for analyzing temporal trends in cut and fill for integrated shoreline and bathymetry data sets (Byrnes and Hiland 1994) provide an automated approach for assessing coastal sediment budgets. In the analysis performed by the U.S. Army Engineer District, Wilmington (1990), volume change data for the ebb-tidal shoal were estimated by calculating differences among discrete areas represented by an average of a number of bathymetric data points rather than using the entire data set and subtracting surfaces. Analysis of change associated with entire data sets using recently developed surface modeling software provides a more accurate estimation of change, particularly in an area as critical as a navigation entrance. Of course beach profile data, integrated with shoreline position data, could be analyzed in a similar manner. Probably the most critical estimated parameter in a sediment budget analysis is the longshore transport rate. For the study at Beaufort Inlet and others (e.g., Headland, Vallianos, and Sheldon 1987), wave energy flux is calculated at the boundaries of sediment budget compartments for determining the potential rate of longshore sediment transport. Shoreline change numerical models provide a more realistic assessment of these rates because model calibration is dependent upon historical shoreline position data. In other words, potential sediment transport rates must be consistent with shoreline change data to produce reliable model output. Consequently, if model calibration is successful, longshore sediment transport rates at sediment budget reach boundaries would be more reliable than calculated potential transport rates from wave energy flux measurements that cannot be tested for accuracy.

4-4. Shoaling Rates

As noted in the previous discussion, two primary components of the sediment budget analysis were channel dredging and maintenance associated with Back Sound and the ebb-tidal shoal at Beaufort Inlet. Because sediment from these types of areas often represents large annual volume changes within the budget, measurement and prediction of shoaling is critical to planning and design of navigation improvements. Economic feasibility of any navigation project depends to a large extent on future channel dredging needs, and accurate prediction of sedimentation rates is a critical part of project planning. Due to the significance of this parameter related to sediment budget determinations and operation and maintenance procedures, a brief discussion is presented below regarding techniques used for predicting shoaling rates. Portions of the following discussions are taken directly from Sorensen (1992).

a. Prediction techniques.

(1) There are many analytical and empirical methods for shoaling rate prediction (Sorenson 1992), but there are no widely accepted techniques. Many of the empirical methods are site-specific, and the theoretical methods often contain simplifying assumptions which limit their applicability. Calculation of shoaling rates depends on assumptions in the method applied and coastal processes in the region of interest. For the purpose of classifying sedimentation processes, a navigation channel from offshore into the back bay or harbor region may be subdivided into four sections. The first is the offshore section located seaward of the surf zone; and the second is the offshore section in the surf zone, but seaward of the region in which significant inlet-induced ebb/flood tidal currents control sediment movement. Depending on inlet entrance geometry and wave climate, the second section may not exist. The portion of the inlet in which sediment transport and resulting channel conditions are dominated by flow through the entrance is the third section. The fourth section is in the harbor interior in which turbulence levels and current velocities are reduced and net deposition of sediment transported into the back bay or harbor takes place.

(2) In the sediment budget example presented herein, the U.S. Army Corps of Engineers, Wilmington District (1990) used historical data to assess the magnitude and rate of shoaling for the Beaufort Inlet entrance channel by evaluating dredging records and bathymetric surveys. This procedure works well; however, its applicability is limited to one area with an excellent record of historical information. If a study were being undertaken in an area with sparse data coverage, the prediction technique would decrease in reliability with proportion to data availability. Clearly, a universal prediction technique based on dynamic processes influencing sedimentation at entrances would be most useful for any inlet system. However, the complexity of sediment-flow interaction at inlet channels has limited the effectiveness of analytical techniques.

(3) The offshore and surf zone sections of the harbor will be discussed herein. For additional discussion of wave and tidal flow-controlled stability conditions at inlets, the reader is directed to Bruun (1978), Escoffier (1977), Jarrett (1976), and Sorensen (1977). Gole, Taraport, and Gadre (1973); Lin and Mehta (1989); Marine Board (1983); and McDougal and Slotta (1986) discuss sedimentation in interior channels and docking slips.

b. Example application - offshore (nonbreaking conditions).

(1) Kadib (1970, 1976, 1991) developed a simple and rational method based on theory and laboratory studies for describing shoaling in dredged channels given nonbreaking wave and current data in the vicinity of the channel. The method was field verified by monitoring the sedimentation rates at a test trench at Morro Bay Harbor entrance in California (Kadib 1993). Kadib's method first assumes that the basic flow field near a channel may be described with two primary processes: 1) a steady current with an average velocity u_1 at water depth d_1 (by continuity, this current will have a velocity u_2 at d_2), and 2) a maximum oscillatory current at the bed due to wave action. These processes were considered the most important factors contributing to sediment movement near a channel. Kadib took this basic premise and, given wave height, wave period, and wave length, calculated bed load and suspended load transport rates using transport relationships developed by Einstein (1950, 1972) and Abou-Seida (1965). The bed-load transport rate Q_b was determined as a function of the sediment concentration in the bed layer C_a and the local current velocity near the bed u_c. Assuming that bed load takes place within a certain bed layer, the concentration of suspended sediment C_h at a distance h above the bed can be determined (Einstein 1950). Once this value is determined, the total suspended load Q_s on the updrift side of the channel and inside the channel can be estimated.

(2) To calculate the rate of sediment deposition per unit width of channel (Q_d), Kadib assumed two primary processes would take place as sediment transported in the direction of a channel encounters the channel. First, the

channel will act as a sand trap for bed load, and second, the current carrying suspended load on the updrift side of the channel will reduce its capacity across the channel due to a decrease in the steady flow velocity, depositing sediment in the channel. Thus, the channel shoaling rate can be represented as the difference between the rate of transport of suspended load reaching the channel (Q_{s1}) and the transport rate across the channel (Q_{s2}), plus the rate of bed-load transport at the channel edge (Q_b), or

$$Q_d = (Q_{s1} - Q_{s2}) + Q_b \tag{4-4}$$

Although rather simplified in context, this approach provides a reasonable analytical technique for estimating channel shoaling rates for noncohesive sediment. In addition, it is not specific to a given inlet environment and thus has greater utility towards understanding and predicting rates of shoaling in channels.

c. Example applications - surf zone (breaking conditions).

(1) The SPM (1984) summarizes procedures for predicting longshore sediment transport rates in the surf zone. Given representative wave conditions for a period of time, the longshore transport rate can be calculated as a volumetric transport rate, or as an immersed weight rate. The SPM energy flux method empirically relates the wave power and longshore transport; however, the mechanics of sediment transport are not considered. Komar (1977) uses a relationship that considers both wave action to suspend sediment and wave-induced longshore current to transport sediment. Although equivalent to the SPM approach, Komar's method does have an advantage since it separates out wave and current effects which may be individually evaluated at points adjacent to and in the channel to calculate respective transport rates and resulting net channel deposition rate. The Komar and SPM methods require similar information: knowledge of the incident wave height, period, and angle with respect to the shoreline at the breaker point; water depths in and adjacent to the channel; sediment density; and an estimate of the in-place porosity of the sediment.

(2) Galvin (1979) developed a simple procedure to examine shoaling at Moriches Inlet, New York. The method estimates the portion of the approaching longshore surf zone sediment transport that will deposit in a channel cut across the bar. The channel cut is assumed to be around an inlet entrance whose ebb tidal flow affects the deposition rate in the bar channel. The U.S. Army Engineer District, Wilmington (1980) also developed a method for predicting the shoaling rate in a channel dredged across the bar offshore of a tidal inlet. A regression analysis of field data from four North Carolina inlets was conducted to relate the bar cut siltation rate with three influencing factors; ebb tidal flow energy, incident wave energy, and sediment entrapment potential, which depends on channel depth.

d. Empirical methods.

(1) Purely empirical methods available for sedimentation prediction do not consider wave and current conditions or local sediment characteristics, but make projections based on historic dredging records for the existing channel. These methods relate previously dredged volumes to time elapsed and pertinent channel geometry features.

(2) Vincente and Uva (1984) present a method that assumes the siltation rate is proportional to the difference between the existing bottom elevation in the channel section and the equilibrium bottom elevation in the channel section for which no deposition will occur. Trawle and Herbich (1980) applied the "volume of cut" procedure to six Atlantic, gulf, and Pacific coast harbor entrance channels where adequate historic dredging records were available. The analysis related percent increase in the volume of cut from the previous channel dimension to the new channel dimension, which therefore indicated a subsequent increase in the dredging requirement.

(3) The U.S. Army Engineer District, Portland (Hartman 1977) developed a method from historical surveys and dredging records. The empirical method predicts controlling dimensions in a navigation channel which result from dredging activities at different times and depths. It assumes that a structurally controlled entrance will have infill or scour rates for a specific depth under similar ocean and river conditions, and that ocean and river conditions are constant during any one month, year to year. A table of shoaling rates is developed, and a "typical" natural channel control dimension curve is generated.

e. Concluding remarks.

(1) Accurate analytical predictions of channel shoaling rates are difficult. This difficulty arises primarily for two reasons: sedimentation processes in navigation channels are complex, and thus development of accurate analytical techniques is difficult; and reliable estimations require a significant amount and variety of input data. An alternate approach to analytical predictions is to employ purely empirical techniques using historic data on

deposition at the project channel or a nearby channel with similar characteristics.

(2) Several methods were discussed herein for the purpose of giving the reader a brief overview of shoaling rate prediction techniques. The broad applicability of these and other methods is presently under investigation at the Coastal Engineering Research Center. The reader is cautioned that, although a given method may be very accurate at one inlet, its application to other locations may result in unreliable predictions. For a more detailed description of the methods, their development and assumptions, the reader is directed to Sorenson (1992).